Modeling Lunar Partnerships to Accelerate Commercial Development

**Brad Blair, David Cheuvront,
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NewSpace Analytics

6 June, 2018
Commercial Space Telecon, Space Portal - NASA Ames Research Center

Status Update

The NASA Emerging Space Office (ESO) selected a proposal entitled **PPP framework for multi-commodity lunar ISRU** for award under NRA Solicitation NNA15ZBP0001N-B1.

PI: Brad Blair
Co-I: David Cheuvront
Consultants: Hoyt Davidson and Hannah Rens

Existential comments (thanks, Lynn)

- Unless something catastrophic happens, there is a potential to expand into space forever using material and energy resources
- The current pool of assets over next 50 years is the Moon, Mars and asteroids
- Costs from Earth stack exponentially in an expendable paradigm
- ISRU linearizes costs - where it crosses the line is interesting
- If there is a lunar station, people will visit it X times per year, but it goes on forever and it expands
- Mars every 2 years, and it goes on forever
- Asteroid inputs to the Earth economy go on forever after a calculable threshold
- What is the risk of doing nothing? What is the risk of losing the opportunity?
- If we succeed with a demo program, it gets everything started
- A calibrated and sufficiently detailed model can identify the point where commercial crosses the line

The Innovator's Dilemma

- A heritage integrated ISRU model has the right structure
- Innovator's Dilemma: What is needed? (the new stuff) and What can be upgraded later?
- The primary goal is connecting the technical content with an enterprise model – one with switches and dials
- Technical numbers can be upgraded later
- The FY02 and FY04 models provide a useful scaffold to connect commercial ideas and a PPP tool to a heritage NASA ISRU-supplied lunar base study

- There is a sense of urgency (three strikes and you are out) – we really have 2.5 years until the next potential reset

- I get to make mistakes in a friendly but firm support system (the weekly telecons)

The Opportunity

A robust, **private-sector commercial lunar ecosystem** will prove invaluable to NASA, *provisioning* propellant, life support consumables and other *materials* to NASA as one customer among many. This would *increase the robustness* of NASA's human space exploration missions by providing sustainable, affordable, complementary options that *reduce* NASA's science and spaceflight *costs*.
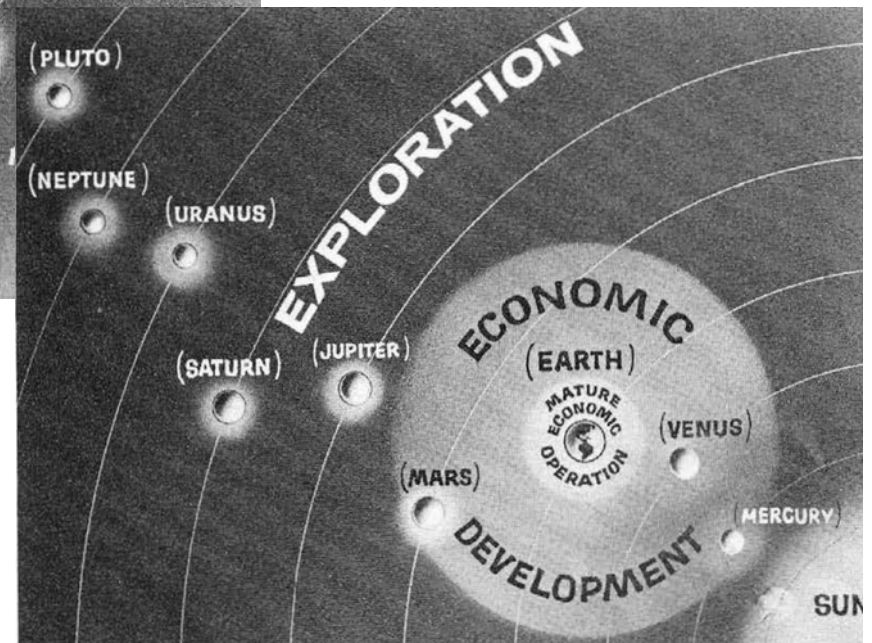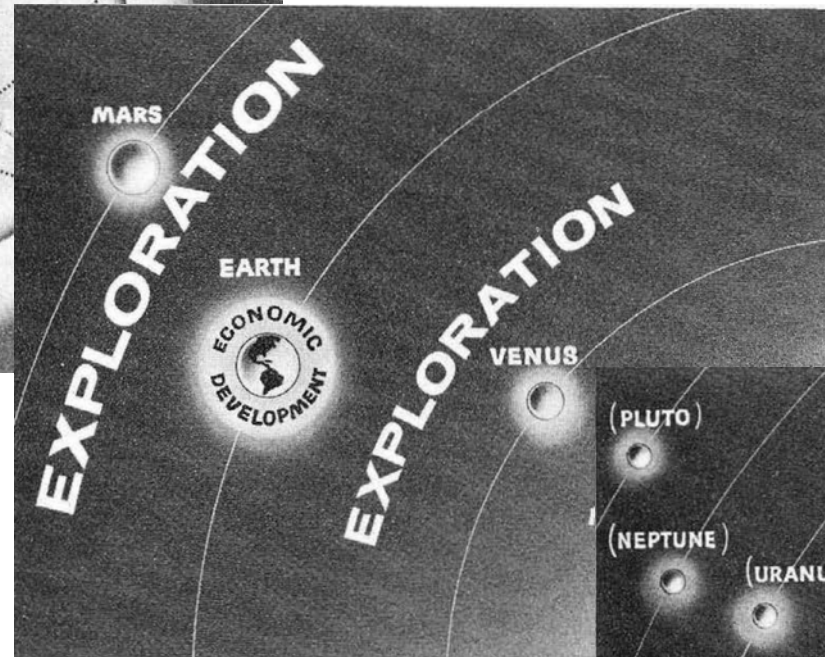
A commercial-off-the-shelf (COTS) approach could also **lower the risk of NASA program failure and/or requirements creep** that typically accompanies cyclical regime change – which is especially troubling for long duration programs (indeed, a lack of fully considering economic factors may be the leading cause of agency regime change).
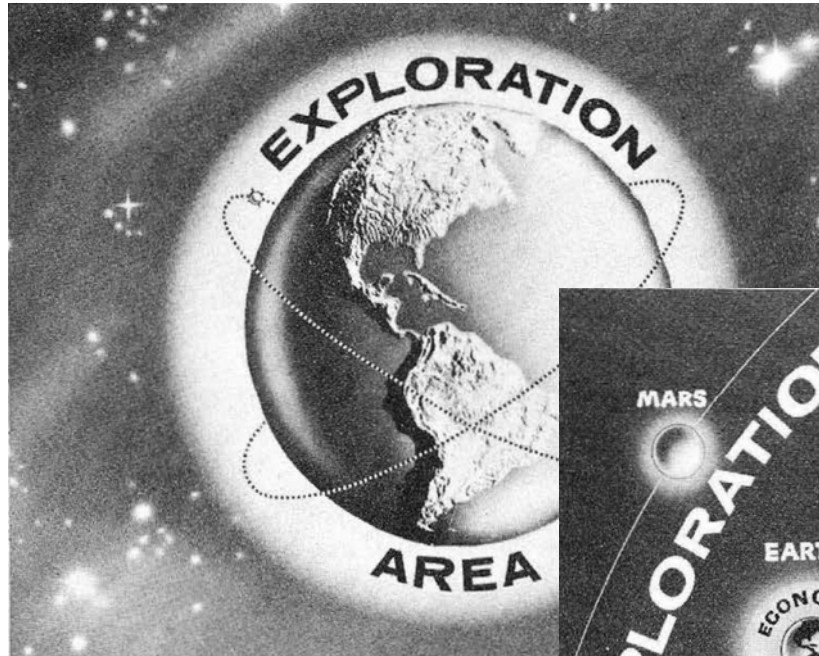
Ralph Cordiner, 1961

Stages of Exploration and Mining

Table I

Mineral asset development stages (VALMIN, 2005; SAMVAL, 2009)

Project development stage	Criterion
Exploration areas	Mineralization may or may not be defined, but where a Mineral Resource has not been identified.
Advanced exploration areas	Considerable exploration has been undertaken and specific targets identified. Sufficient work has been completed on at least one prospect to provide a good geological understanding and encouragement that further work is likely to result in the determination of a Mineral Resource.
Pre-development / resource	Mineral Resources and/or Mineral Reserves were identified and estimated. A positive development decision has not been made.This includes properties where a development decision has been negative and properties are either on care and maintenance or held on retention titles.
Development	Committed to production but not yet commissioned or not initially operating at design levels.
Operating	Mineral properties, in particular mines and processing plants, which were fully commissioned and are in production.

Table II

Rule-of-thumb confidence intervals for technical studies (at assumed 90 per cent confidence)

Measure/item	Scoping study	Pre-feasibilitystudy	Final feasibility study
Cost accuracy	±25%-50%	±15-25%	±10-15%
Cost contingency	30-50%	15-30%	<15%
Proportion of engineering complete	<5%	<20%	<50%
Resource categories	Mostly Inferred	Mostly Indicated	Measured and Indicated
Reserve categories	None	Mostly Probable	Proved and Probable
Mining method	Assumed	General	Optimized
Mine design	None or high-level conceptual	Preliminary mine plan and schedule	Detailed mine plan and schedule
Scheduling	Annual approximation	3-monthly to annual	Monthly for much of payback period
Risk tolerance	High	Medium	Low

PPPs can Maximize Benefits

Public Benefits

-Ops Risk Reduction (consumables + propellant)
-Lower Costs (off-budget capital)
-Programmatic Risk Reduction (Insurance)

Private Benefits

-Economic Profit
-Risk Appetite (aggression)
-Historical Legacy

Constellation, Circa 2007

Ichthyostega, Circa 374–359 Ma

Study Objectives

Primary Study Objective:

- Build and utilize a *commercial lunar mining* model to estimate the **effectiveness of PPP scenarios** in *accelerating* lunar development

Secondary Objectives:

- Examine lunar resource *byproduct scenarios* that may be synergetic or of low incremental cost to obtain high economic benefit
- Identify comparisons to *terrestrial mining* activities, where byproducts often generate more operating profit than the primary commodity

Stretch goal: This work could also *generate a method* to steer near term prospecting and ISRU technology demonstration missions toward 'commercially useful results' by using a risk analysis framework to 'buy down' uncertainty

The Challenge

What makes you think you can do all of that?
- We had a head start
- We have a pretty good network to ask for help
- We kept the "core innovation" simple
- We have a really good team
- We have a really good reason to do it

Motivation
- We could wait and ask for a proper budget to 'do the job right'
- It might delay PPP readiness for another year or more
- We need to act fast to converge and move forward (three strikes)
- A motivated and capable small team can sometimes make big
    progress

The Team

Core Team
- Brad Blair
  - Built first commercial ISRU model in 2002
  - Background in mining and economics
- Dave Cheuvront
  - 40+ years aviation & space, retired NASA, multi-disciplines
  - ISS development, R&M, T&V; exploration system engineering, S&MA
- Hannah Rens
  - 2x SSDC winner, UT Austin Sophomore
- Hoyt Davidson
  - Near-Earth LLC, 400p. report in 2010 on Commercial Space

Extended Team
- Space Portal: Lynn Harper, Bruce Pittman, Allison Zuniga
- Space Settlement Specialist Anita Gale
- LaRC Roger Lepsch (landers & space transport)
- KSC Edgar Zapata (commercial costing)
- Tony Muscatello, Nathan Davis (chemical engineering / extractive metallurgy)
- George Sowers (lunar mining systems design / commercial landers)
- Guest Appearances: Dan Rasky, John Patterson, Richard Godwin, Geoff Sheerin, Daniel Faber, Jim Keravala, Bernard Kutter, Dennis Stone, Angel Abbud-Madrid, Bruce Cahan, Koki Ho

The Head Start

FY02 Lunar ISRU Economic Model (CSM – Mike Duke)

- Solved for feasible conditions for lunar commercial investment

FY04 RASC ISRU Study

- Two NASA Centers
- Two Universities
- Canadian Team
- Multiple Consultants

- Absorbed into CE&R / VSE

The Case for Commercial Lunar Ice Mining

by

Brad R. Blair, Javier Diaz, Michael B. Duke,
Center for the Commercial Applications of Combustion
in Space, Colorado School of Mines, Golden,
Colorado

Elisabeth Lamassoure, Robert Easter,
Jet Propulsion Laboratory, Pasadena, California

Mark Oderman, Marc Vaucher
CSP Associates, Inc., Cambridge, Massachusetts

December, 2002

Table 4.2. Model versions relative to baseline.

Version	Description	Summary
0	Architecture 1&2 Baseline. All assumptions set to most conservative level.	Baseline
1	Baseline w/ No Non-Recurring Investments. (assumes that the public sector pays for design, development and first unit cost)	Remove DDT&E from Baseline
2	No Non-Rec. Investments + Reduce the production cost of all elements by 30%.	Add 30% Production Cost Reduction
3	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith from 1% to 2%.	Add 2x Lunar Water Concentration
4	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith + Double demand.	Add 2x Demand
5	No Non-Rec. Investments + Reduced production cost + Increase concentration of Water in Lunar Regolith + Double demand + Price Increase	Add 1.25x Price

Table 4.3. Model results (key financial metrics) by version for Architectures 1 and 2.

	Year 1 Return on Equity		Project Rate of Return		Net Present Value	
	Arch 1	Arch 2	Arch 1	Arch 2	Arch 1	Arch 2
Version 0	N/A	N/A	N/A	N/A	$ (5,275)	$ (5,006)
Version 1	-30.3%	-30.5%	-11.9%	-11.9%	$ (553)	$ (561)
Version 2	-9.8%	-10.1%	-5.0%	-5.2%	$ 255	$ 240
Version 3	-2.3%	1.6%	-1.7%	-0.3%	$ 593	$ 726
Version 4	15.0%	15.2%	6.2%	5.9%	$ 2,484	$ 2,461
Version 5	26.1%	26.3%	12.8%	12.6%	$ 4,156	$ 4,134
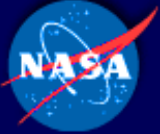
Space Transportation Architecture Based On ISRU Supplied Resources Study
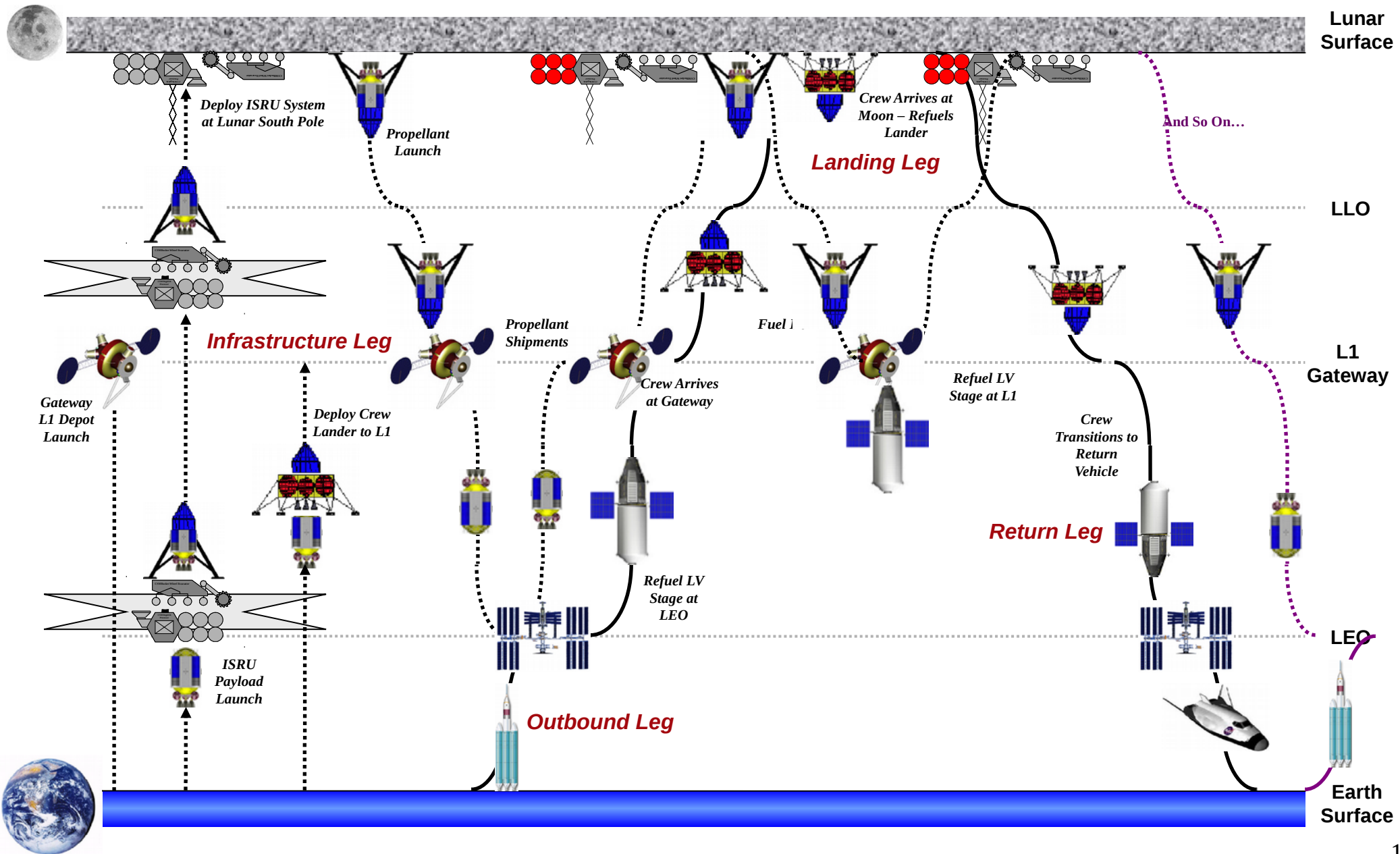
**Scott Baird,
Kris Romig,
Jerry Sanders
JSC**

January 2004

Executive Summary

- **Project Title: Space Transportation Architecture Based On ISRU Supplied Resources Study**
- **Purpose**
  - Identify ISRU-based space transportation scenarios and compare them to Earth supplied scenarios to provide architecture trade crossover points for cost, mass, and schedule
  - Identify architecture sensitivities and drivers
  - Identify key technology needs/drivers to help prioritize ISRU technology development

- **Scope**
  - Develop & model ISRU production and product transportation and storage architecture options
  - Define & model elements for space transportation architecture options
  - Define & evaluate emplacement and buildup scenarios
  - Model & evaluate architecture option operations, costs, and business/commericial potential
  - Perform technology driver and cost analysis sensitivity studies

- **Study Summary: Preliminary Findings & Conclusions**
  - Development of ISRU and transportation elements still in work (study end date 6/04)
  - Earth-Moon L1 point is most optimal position for propellant depot for Earth orbit satellite servicing and satellite delivery tugs from Low Earth Orbit (LEO) to Geostationary Orbit (GEO)
  - Commercial potential of combined ISRU propellant/L1 Depot could significantly influence architecture and reduce cost to NASA

- **Application to NASA Future Mission Needs**
  - ISRU and transportation element concepts, models, and databases developed in this study can be applied to future Design Reference Missions (DRMs)
  - In-situ production of mission critical consumables (propellants, life support, fuel cell reagents, science gases) provides early mission benefits with minimal infrastructure requirements

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FY04 Lunar ISRU Architecture

Lunar Surface

Deploy ISRU System at Lunar South Pole

Propellant Launch

Crew Arrives at Moon – Refuels Lander

And So On…

Landing Leg

LLO

Infrastructure Leg

Propellant Shipments

Fuel

L1 Gateway

Gateway L1 Depot Launch

Deploy Crew Lander to L1

Crew Arrives at Gateway

Refuel LV Stage at L1

Crew Transitions to Return Vehicle

Return Leg

ISRU Payload Launch

Refuel LV Stage at LEO

LEO

Outbound Leg

Earth Surface

Advancing the State of the Art
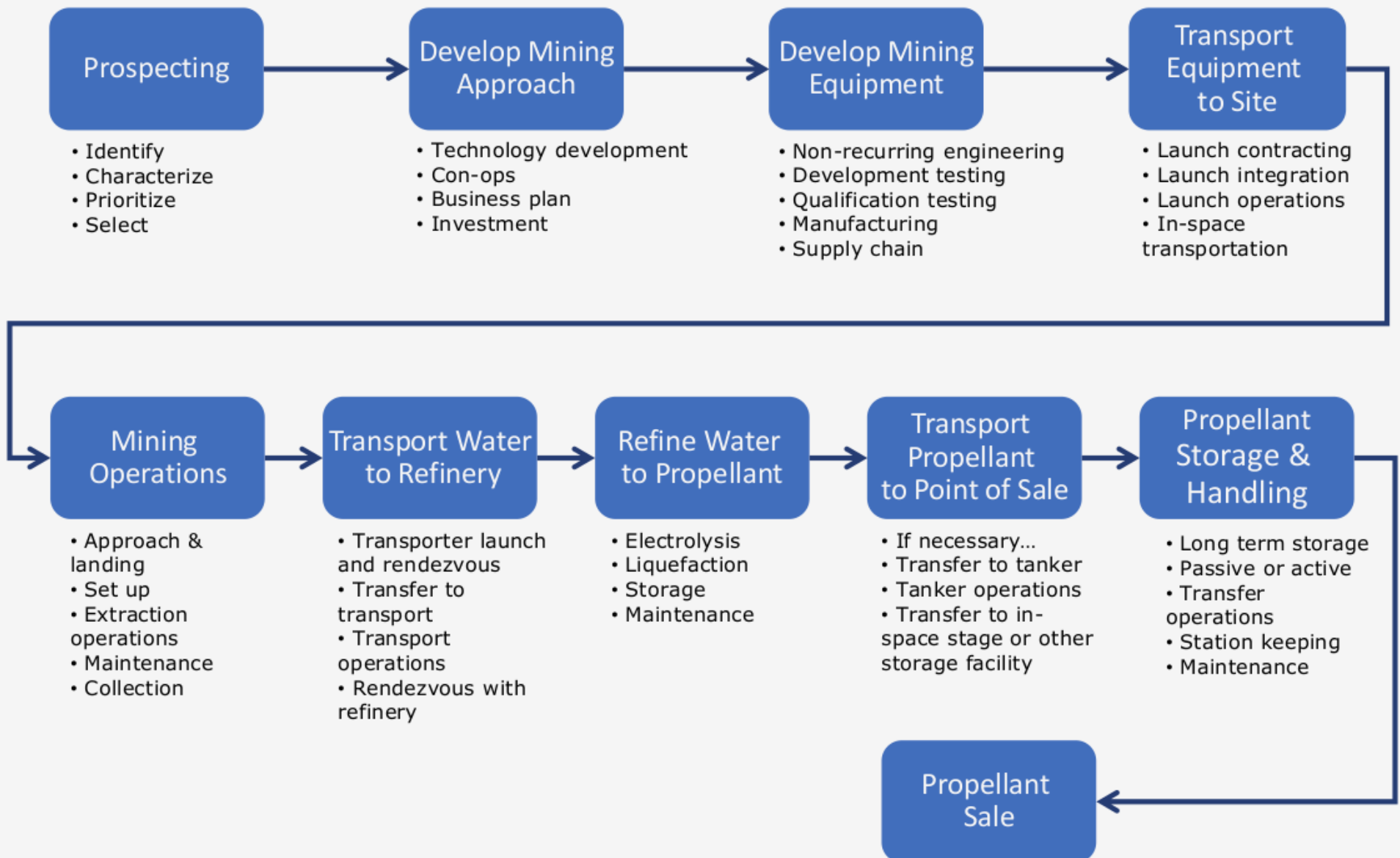
Model Upgrades

Heritage (FY04)
- Reusable Landers, Transfer Stages, CEV
- Lunar ISRU
  - Nitrogen from regolith
  - Ice from poles
  - Glass
  - Solar Cells
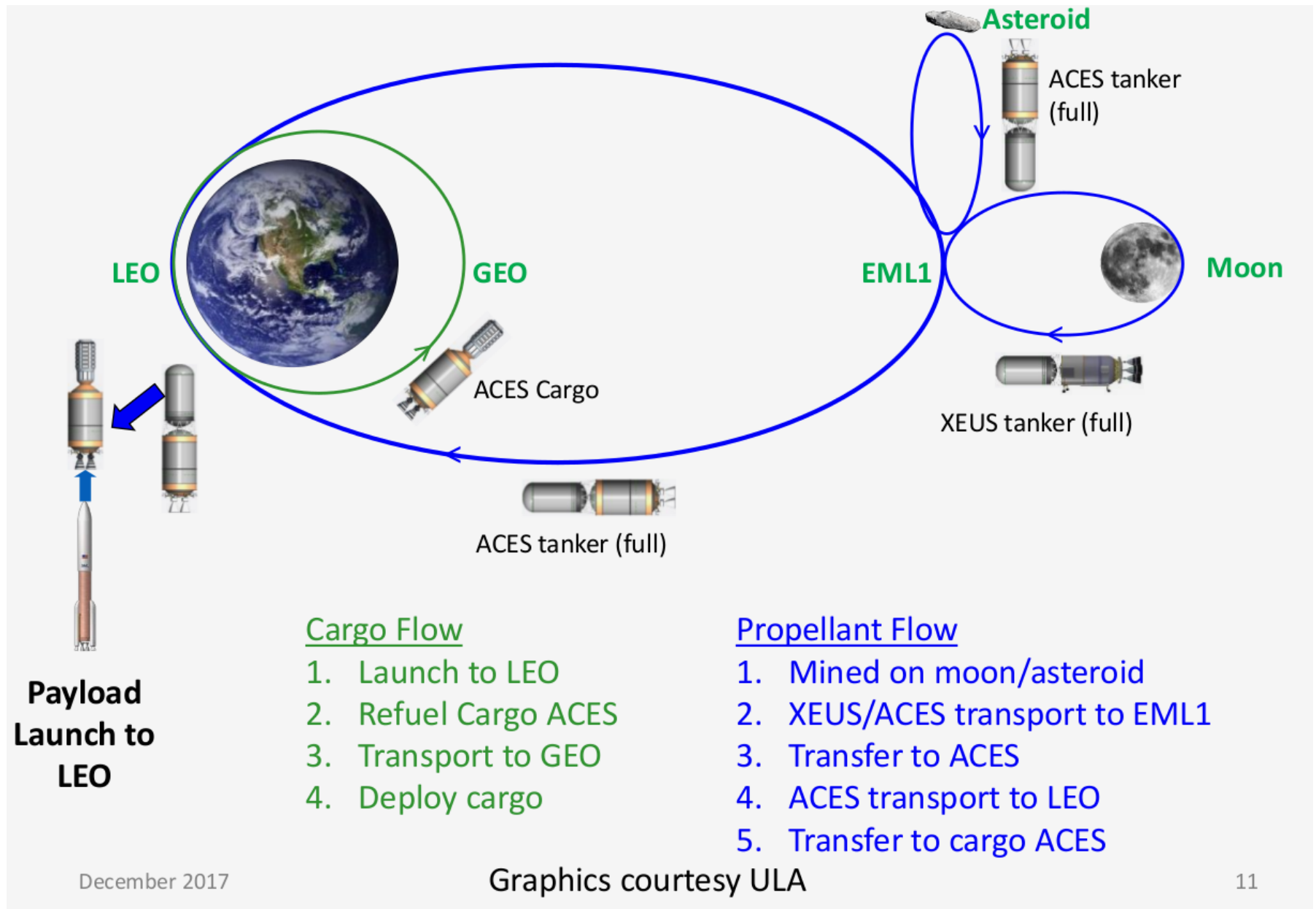- Cost model (NAFCOM, SOCM, Launch & Logistics)

Upgrades in Place
- ISRU Plant
  - +mixed volatiles
  - +metals
  - +CSM/ULA mining model
- Demand Scenarios (Cislunar 1000, Mars Exploration, CH4, Defense propellant)
- Price Forecast
- Competitive Scenarios (Market share & Price)
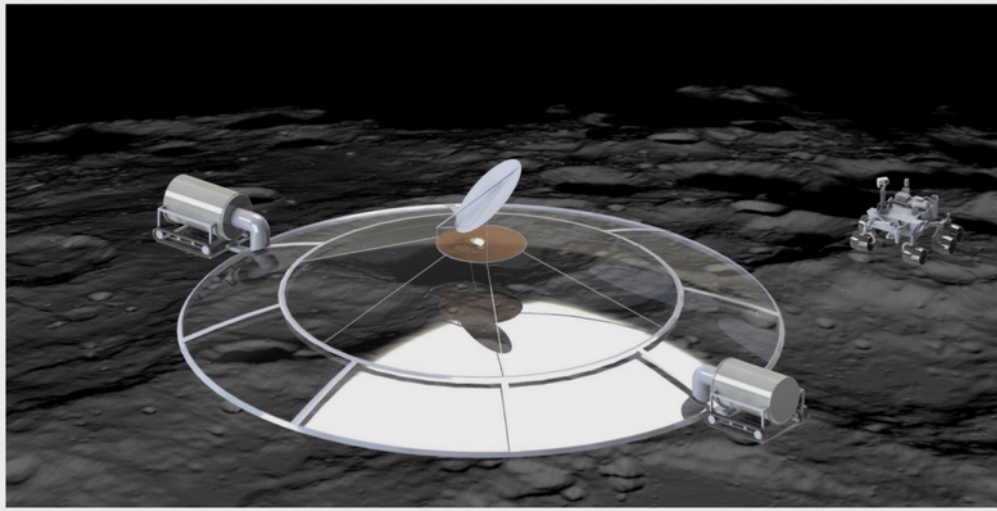- Enterprise Layer
- PPP options

CSM-ULA Mining Architecture

Prospecting
- Identify
- Characterize
- Prioritize
- Select

Develop Mining Approach
- Technology development
- Con-ops
- Business plan
- Investment

Develop Mining Equipment
- Non-recurring engineering
- Development testing
- Qualification testing
- Manufacturing
- Supply chain

Transport Equipment to Site
- Launch contracting
- Launch integration
- Launch operations
- In-space transportation

Mining Operations
- Approach & landing
- Set up
- Extraction operations
- Maintenance
- Collection

Transport Water to Refinery
- Transporter launch and rendezvous
- Transfer to transport
- Transport operations
- Rendezvous with refinery

Refine Water to Propellant
- Electrolysis
- Liquefaction
- Storage
- Maintenance

Transport Propellant to Point of Sale
- If necessary...
- Transfer to tanker
- Tanker operations
- Transfer to in-space stage or other storage facility

Propellant Storage & Handling
- Long term storage
- Passive or active
- Transfer operations
- Station keeping
- Maintenance

Propellant Sale

CSM-ULA Transportation / Conops

Cargo Flow
1. Launch to LEO
2. Refuel Cargo ACES
3. Transport to GEO
4. Deploy cargo

Propellant Flow
1. Mined on moon/asteroid
2. XEUS/ACES transport to EML1
3. Transfer to ACES
4. ACES transport to LEO
5. Transfer to cargo ACES

CSM-ULA Design Elements

Capture Tent

Cold Traps

- Function
  - Freeze and contain sublimated water vapor
  - Transport (with mobility system) ice to processing facility
- Concept
  - Three (to match number of ice haulers & allow parallel operations)
  - Aluminum cylindrical tank with hemispherical or elliptical domes
  - 3 m X 1.5 m
  - 300 kg
  - Holds 500 kg ice in the form of frost/snow
  - 1.1 m diameter pipe to connect to capture device and processing plant
    - Non-sealing closure
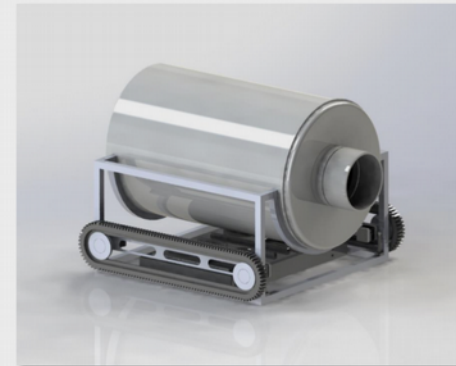
Ice hauler (with cold trap)

Propellant Storage Concept

- Storage system
  - Spent XEUS stages
  - Assume three (provides volume to fuel XEUS and tanker with 50% margin)
- Liquification, conditioning and transfer equipment kitted prior to XEUS launch
- Mass = 1000 kg per XEUS, 3000 kg total (accounted for under propellant processing)

XEUS

Power System Concept

- PV array
  - Size determined by focusing ability of rim mirror/concentrator
  - Pointable
  - 1.5 Mw power output
- Power conditioning & storage system
- Charging station for mobility systems
- Mass = 4000 kg
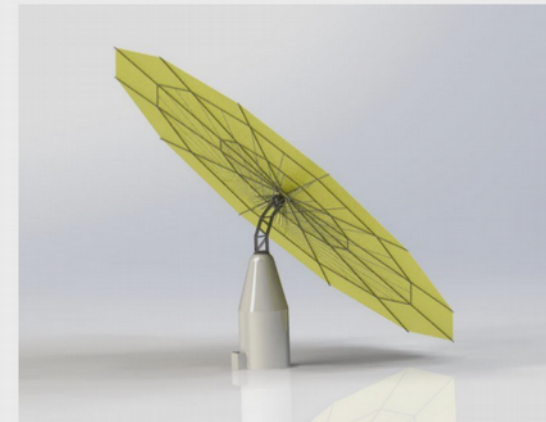
LCROSS Results for Water and Other Volatiles

Table 1. Summary of the total water vapor and ice and ejecta dust in the NIR instrument FOV. Values shown are the average value across the averaging period, and errors are 1 SD.

Time (s)	Water mass (kg)		Dust mass (kg)	Total water %
	Gas	Ice		
0–23	82.4 ± 25	58.5 ± 8.2	3148 ± 787	4.5 ± 1.4
23–30	24.5 ± 8.1	131 ± 8.3	2434 ± 609	6.4 ± 1.7
123–180	52.5 ± 2.6	15.8 ± 2.2	942.5 ± 236	7.2 ± 1.9
Average	53 ± 15	68 ± 10	2175 ± 544	5.6 ± 2.9

Table 2. Abundances derived from spectral fits shown in Fig. 3. The uncertainty in each derived abundance is shown in parenthesis [e.g., for H_2O: 5.1(1.4)E19 = $5.1 ± 1.4 \times 10^{19}$ cm^{-2}] and was derived from the residual error in the fit and the uncertainty in the radiance at the appropriate band center.

Compound	Molecules cm^{-2}	% Relative to $H_2O(g)$*
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

*Abundance as described in text for fit in Fig. 3C.

Colaprete et al. (2010)

Polar Mining
& Volatile Production

Polar Ice Production Model

- PROCESSING UNIT
  - PRIMARY HEATING REACTOR
  - ➔ FRACTIONAL CONDENSATION DISTILLATION UNIT
  - ➔ CARBON COMBUSTION UNIT
  - ➔ SABATIER REACTOR
  - ➔ SULFUR EXTRACTION
  - WATER ELECTROLYSIS
  - OXYGEN LIQUEFIER
  - HYDROGEN LIQUEFIER
  - ➔ NITROGEN LIQUEFIER
  - ➔ METHANE LIQUEFIER
  - ➔ AMMONIA LIQUEFIER
  - ➔ MERCURY SEPARATOR (centrifuge)

- MINING EQUIPMENT
  - Front Loader
  - Hauler
  - Low Pressure Feed Hopper
  - High Pressure Feed Hopper

- TANK FARM
  - WATER TANK
  - OXYGEN TANK
  - HYDROGEN TANK
  - ➔ NITROGEN TANK
  - ➔ METHANE TANK
  - ➔ AMMONIA TANK
  - ➔ MERCURY TANK
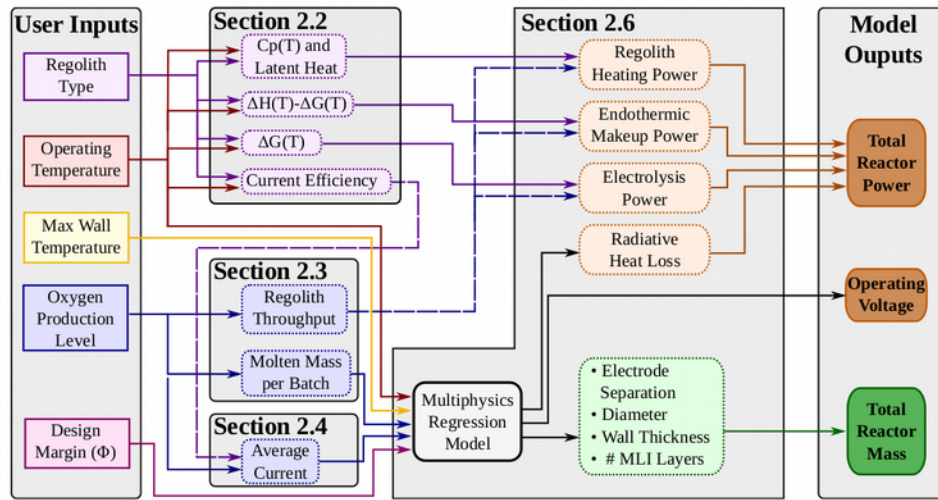
Molten Oxide Electrolysis modeling
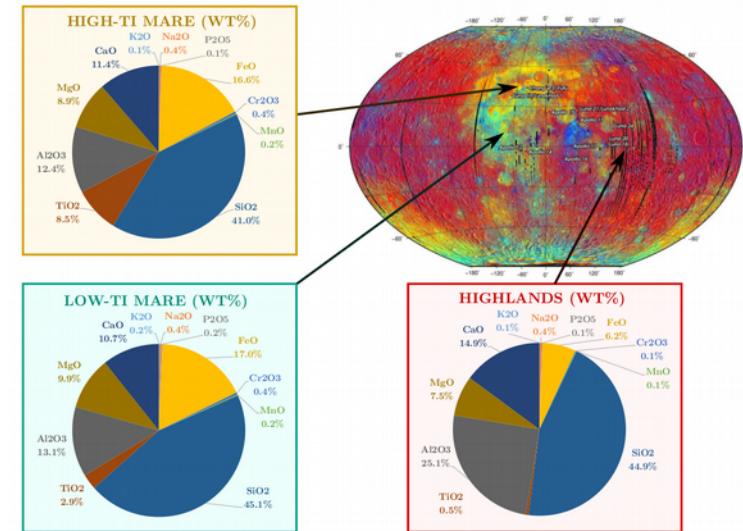

Figure 2.1 of [Schreiner and Hoffman, 2015]

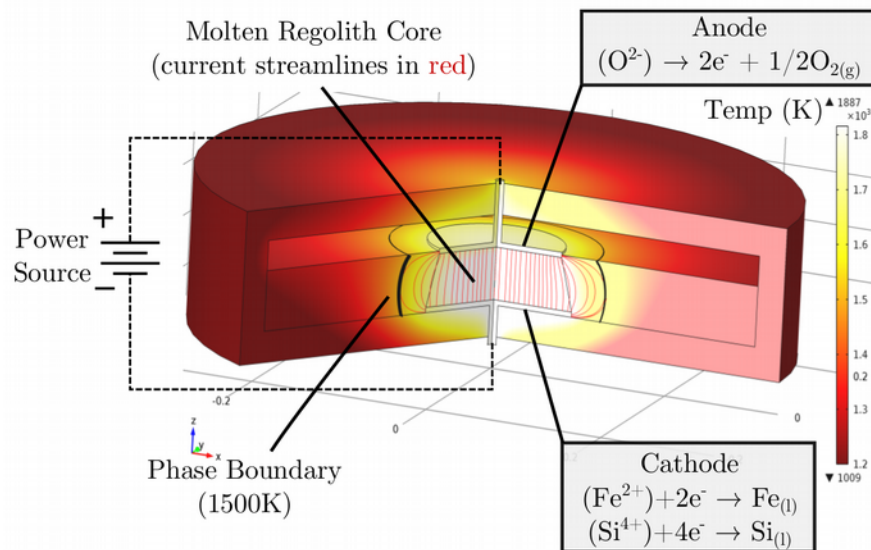Figure 2.2 of [Schreiner and Hoffman, 2015]
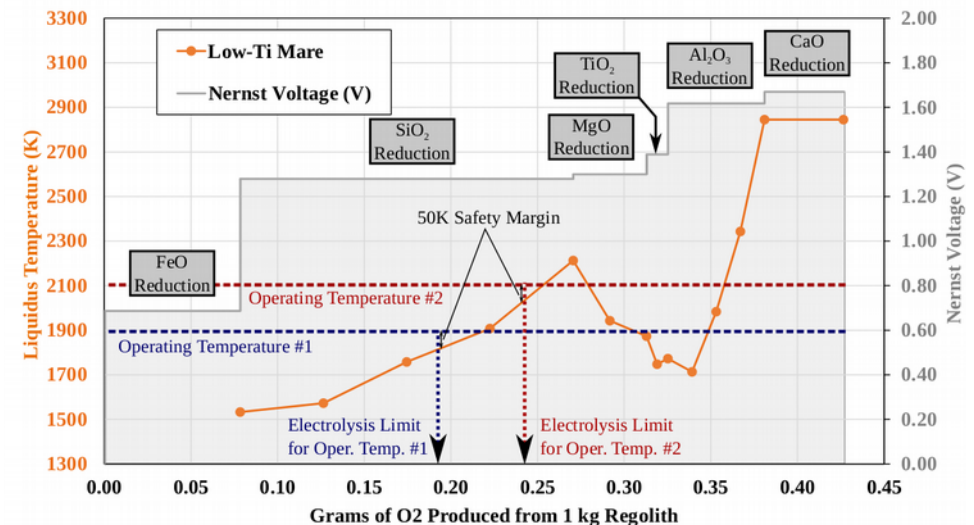

Figure 1.2 of [Schreiner and Hoffman, 2015]

Figure 2.9 of [Schreiner and Hoffman, 2015]
http://ssl.mit.edu/files/website/theses/SM-2015-SchreinerSamuel.pdf

Public Private Partnerships

A rich set of public-private partnership (PPP) options are available to government. A tool is needed to help select the PPP strategy that could *maximize the rate of lunar commercialization* by **attracting private capital** into the development of critical **infrastructure** and robust **capabilities** that directly serve government needs.

A successful lunar industrial development program would be good for the country, offering a path to **revitalize the US economy** by opening up whole new worlds of resources while **increasing national employment** in aerospace and other high technology sectors.

Existing and candidate PPP options
(Davidson, 2010b)

Investor Risks	LCRATS	NASA Contracts	Tech Demo Missions	SAAs	Patent License	CRADA	SBIR / STTR	IPP Seed	Centennial Challenges	COTS Type
Technical: Developing new technologies	High		High	High	High	High	Moderate	High	High	Moderate
Technical: Manufacturing difficulty	Moderate		Moderate	Moderate	Moderate	Moderate		Moderate	Moderate	High
Market: Size	High	Moderate		Moderate	Moderate	Moderate			Moderate	Moderate
Market: Quality and reliability	Moderate									Moderate
Market: Development timing	High	Moderate						High		High
Market: Uncertainty	Moderate							Moderate		Moderate
Financial: Magnitude of capital required	High	High	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate		High
Financial: Timing of capital needs	High							High	Moderate	High
Financial: Uncertainty	Moderate		Moderate					Moderate		High
Financial: ROI hurdle	Moderate	Moderate		Moderate		Moderate	Moderate			High
Political / Regulatory: Policy & budgets	High									High
Political / Regulatory: Regulatory compliance	High									Moderate
Political / Regulatory: Treaties & indemnification	Moderate									Moderate
Perception	Moderate		Moderate	Moderate	Moderate	Moderate			High	High

Investor Risks	LCRATS	Tax Credits	Loan Guarantees	Anchor tenancy	Other purchase agreements	Direct Investment	Government Trust Fund (SPIC)	Super SBIR	Super Competitions	Customer #1 Procurement	Free Flight Challenge	Bounties on orbital debris
Technical: Developing new technologies	High					High		High	Moderate		Moderate	
Technical: Manufacturing difficulty	Moderate					Moderate		Moderate	High			
Market: Size	High			Moderate	Moderate				Moderate	Moderate		High
Market: Quality and reliability	Moderate			High	Moderate				Moderate			High
Market: Development timing	High			Moderate						High	Moderate	High
Market: Uncertainty	Moderate			Moderate	High					Moderate		High
Financial: Magnitude of capital required	High	High	High			Moderate	High	Moderate		Moderate	High	Moderate
Financial: Timing of capital needs	High	Moderate	High				High			Moderate	Moderate	Moderate
Financial: Uncertainty	Moderate	Moderate	Moderate	Moderate		High	High					Moderate
Financial: ROI hurdle	Moderate	High	High	Moderate		Moderate	Moderate		Moderate	Moderate	Moderate	Moderate
Political / Regulatory: Policy & budgets	High	Moderate	High	Moderate	Moderate	Moderate	High					High
Political / Regulatory: Regulatory compliance	High											Moderate
Political / Regulatory: Treaties & indemn.	Moderate											High
Perception	Moderate	Moderate	High	High	Moderate	Moderate	High		High	Moderate	Moderate	Moderate

Davidson, Hoyt, et al. "Supporting Commercial Space Development Part 2: Support Alternatives versus NASA Commercialization Priorities", Near Earth LLC, NASA Contract NNH11CD08D, November 2010, https://www.nasa.gov/sites/default/files/files/SupportingCommercialSpaceDevelopmentPart2.pdf

Enterprise Modeling: Study Goals

1. **<u>Create flexible enterprise modeling tool</u>**
   - Easy link to production models
   - Take market demand time series
   - Take market share and pricing data
   - Take capital expenditure costs
   - Take production & operating costs
   - Assume PPP factors
   - Create financial statements
   - Calculate NPV and IRRs
   - Determine sensitivities

2. **<u>Estimate economic viability of various production models</u>**
   - With varying production processes, byproducts, strategies
   - With varying market demand and pricing assumptions
3. **<u>Estimate optimal PPP support</u>**
   - Required types and levels of support to attract private capital
   - Best alternatives for government

Status vs. Goals

1. **Create flexible enterprise modeling tool**
   - Done: Interface to production models
   - Done: Version 1 of Enterprise model
   - Done: Key PPP parameters modeled
   - Done: Full financial statements
   - Done: Calculates NPV and IRRs
   - CIP: Sensitivity analysis & data tables
   - TBD: Add price elasticity formulas
   - TBD: Add accelerated depreciation
   - TBD: Add more inventory cost methods
   - TBD: Add more equity & debt securities

2. **Estimate economic viability of various production models**
   - Tested conceptually, viability seems possible for some cases
   - Need better cost and market data to run accurate cases
3. **Estimate optimal PPP support**
   - Tested conceptually, PPP support can work
   - Need better cost and market data to optimize PPP structures

4 Big PPP Knobs to Turn

- **Uncertain demand for commodities is biggest challenge to enterprise**
  - Focus: "prime the pump" as 1st customer
 - *Model: Choose unit purchase guarantees by commodity by year*

- **Changing government policy and regulatory risks are existential**
  - Focus: Substantial USG co-investment "skin-in-the-game"
  - Model: Choose % of each CapEx category to be government funded
- **Technical obsolescence and/or competition boost ROI requirements**
  - Fucus: Lower WACC thru USG loan guarantees and rate subsidies
  - *Model: Choose % of total up front capital to be government backed*
- **Operating risks and challenges reduce profit margins**
  - Focus: Tax credits to balance extreme operating risk and high R&D
  - *Model: Choose which expense line items to qualify for credits*

Common Pitfalls and their Results

- Imposing risk requirements after making key decisions
  - Precludes implementation of the most effective options
  - Similar to Value Engineering & Supportability principles
- Focus on a specific risk to the exclusion of others
  - Sub-optimal solutions for integrated end-to-end risk
- Imbalance of risks to different parties
  - Win/lose rather than win/win
- Unappreciated and under-appreciated risks
  - Unprepared to manage the consequences
- Over-design to extent that risk increases
  - Adding complexity to reduce risk
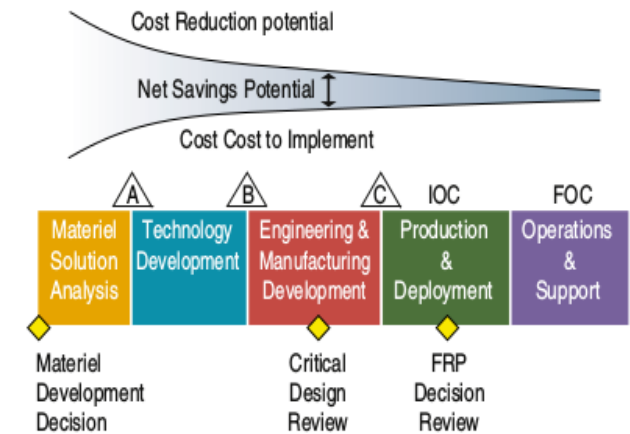
DefenseATL-MayJune-2009-VE-Reed-Mandelbaum
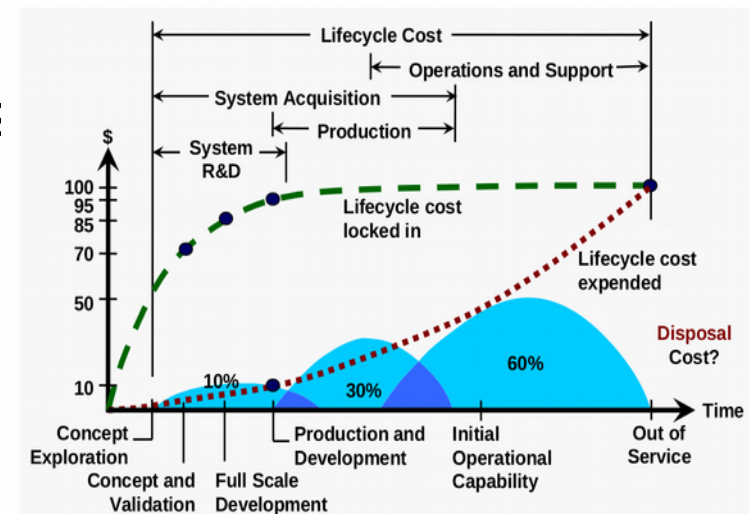
From W. J. Larson & L. K. Pranke (1999) Human Spaceflight: Mission Analysis and Design

Application of Resilient Architecture Concepts *

- "Resilience" - Complex systems that stably operate within their normal design parameters and through unexpected events or changing needs

  - Common interfaces and standards to interconnect components, elements, systems, and sub-systems in multiple ways making them less vulnerable to failures

  - Different kinds of components, elements, and subsystems, provided by different organizations, nationalities, cultures, and individuals

  - Start with small scale tests and demos, develop modular capabilities (e.g., resource location, characterization, extraction, ISRU processing, power, life support, propellant delivery), replicate to increase capacity

  - Adapt in response to failures, evolutionary learning & discovery of new knowledge about what works (or not)/other changing needs.

Integrated Risk Strategies

- Multiple small prospector scouts by multiple providers per launch

- Use of contingency launches and other operations ("M of N" reliability)

- Unused contingency hardware from one mission subsequently assigned as next primary

- Highly manufacturable, upgradeable, modular designs, mfg in quantity

- Standard interfaces and interoperability

- Multiple launches, time-phased to incorporate learning cycles

- Large population of small multiples and high flight rates to leverage reliability growth

- Early revenue-generating flights with cargo prior to crew

- Initial use of polar-capable landers in equatorial region with larger margins

Integrated Risk Strategies (Cont'd)

- Start ISRU production sized for small scale reusable landers or hoppers

- Consider early demo/Minimum Viable Product with LOX only (use terrestrial LH2/fuel)

- Use of reusable landers in non-reusable or terrestrially-resupplied mode until ISRU propellant is available, then resupply it on the lunar surface in an uncrewed demonstration mode

- Scale up ISRU production to practically any level desired by adding more units/capability

- Add the ability to capture by-products at low incremental additional cost to improve economics and enabling additional infrastructure development

- Early depot or stage refueling in LEO with terrestrial propellants so an L-1 depot can be ready when lunar ISRU products are available

- Terrestrial propellant can supplement or make up for any ISRU shortfalls

Costing the Mining Architecture

- Cost + Government contracting is easy to estimate with NAFCOM analogies, but are useful in establishing a conservative baseline

- Commercial costs are hard to predict
  - Bottoms-up approach works, but requires more information that we have
  - Commercial analogies are sparse
  - Cost risk (exceeding budget expectations) is high

- "Assuming that you can keep DOE and NASA from turning them into white collar welfare programs, ..."

Cost as an Independent Variable

- Cost is the new independent variable (George says he can close the biz case but it requires 50k/kg hardware)

- Questions: Does that include SI and gov/biz wraps? Does it include development?

- The PPP model should be able to answer that

References

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